Official English translation

DEVELOPMENT OF FIELD EMITTERS FOR SHORT WAVE MICROWAVE DEVICES AND THEIR INVESTIGATION IN SPbPU: LATEST ACHIEVEMENTS

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Topic and aim. The data on the latest achievements of the authors on the development and investigation of field emitters for electron-beam microwave devices of millimeter and submillimeter wavelengths range are presented. **Methods.** The methods for creating and characteristics of new type cathodes, that are of great practical interest, are described: multi-tip silicon cathodes with two-layer metal-fullerene coatings and multilayer nano-structured cathodes, whose emission is determined by the fields at the contacts of materials with a different work function. Numerical calculations and experimental investigation were carried out to optimize the cathodes and to determine their emission characteristics. The most important features of used experimental setup are as follows: • the operative change of the pressure from the minimal value 10^{-9}–10^{-10} Torr up to 10^{-6} Torr and back is possible; • it is possible to carry out a number of technological operations directly in the vacuum chamber, including the deposition and treatment of coatings; • it is possible to study the emission characteristics of cathodes in the continuous and pulsed modes over a wide range of voltages (up to 15–25 kV) and currents (up to 0.5 A). **Results**. A large number of new results have been obtained which include: • fairly simple and reproducible technologies for creating multi-tip and multilayer emitters have been worked out; • the mechanism of functioning of protective fullerene coatings has been defined; • the optimal structure and morphology of the surface of multi-tip cathodes with metal-fullerene coatings have been determined and the possibility of obtaining the field emission currents up to about 100 mA with the current density up to 0.4 A/cm^2 has been demonstrated; • the optimal structure of multilayer hafnium-platinum cathodes was determined and the possibility of obtaining the emission currents of about 2 mA at an extremely high current density of about 200 A/cm^2 has been demonstrated; • the possibility of a long-term stable operation of the created cathodes at large currents in the conditions of at technical vacuum has been demonstrated. **Discussion**. Summarizing, it can be said that the created and studied cathodes are promising for use in miniature high-voltage electron-beam microwave devices of the millimeter and submillimeter wavelength range.

Key words: field emission, multi-tip cathodes, multilayer cathodes, technical vacuum, ion bombardment, two-layered metal-fullerene coatings, fields of contact potential difference, short-wave electron-beam microwave devices.

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Introduction

Until recently, field emitters were used primarily in ultrahigh-vacuum and low-current electronic devices, functioning at moderate operating voltages. Meanwhile, there are miniature, but high-voltage microwave devices, where it is difficult to use incandescent thermal cathodes, and they attract more and more interest. For example, there are electron-beam devices of short-wave millimeter and submillimeter wavelength range [1, 2].

Effective field emitters have been developed (see, for example, [3–6]), which make it possible to obtain currents of the order of tens of milliamperes and density of field emission currents exceeding or equal to 100–200 mA/cm^2, necessary for these applications.

But, unfortunately, the possibility of long-term operation of the created emitters in high-voltage electronic devices at large currents in conditions of technical vacuum, is not proved. In existing «distributed» multi-tip or blade field emitters, it is possible to reduce the current load to a separate emission center and thus reduce the thermal effects on the emitter associated with the flow of currents through the emission centers. However, it is not yet possible to exclude the destructive effect of ion bombardment, which is intense in the technical vacuum. When using Spindt cathodes [3], attempts were made to reduce the intensity of ion bombardment of the cathode by means of special electron-optical systems that prevent ions from transport channel of electron beam formed by field emitter to hit cathode surface. But this did not exclude the bombardment of the cathode by fast ions generated in the electron acceleration region before entering the transport channel.

In recent years, designs have been developed for miniature field- electron structures with ion emitter protection [7]. The electron-optical system of such structures should exclude impact of ions formed in the structure itself on the cathode, but it is doubtful that the electric fields in such small-sized structures can effectively protect the emitter from bombardment by ions with an energy of more than several hundred volts arising at the electrons acceleration area outside the cathode structure.

In this paper, we will consider field emitters of a new type perspective for use in high-voltage electronic devices operating in technical vacuum conditions.

1. Field emitters with a protective fullerene coating

1.1. Protection of single-tip tungsten emitters. Special coatings that can protect the field emitter from the destructive effect of ion bombardment have been developed by the authors [9–10]. For these purposes, a coating of fullerene C_{60} molecules with a thickness of 2–3 monolayers (ml) was used. A study of the operation of single-tip tungsten emitters with fullerene coatings performed in a field emission projector is described in [8–10]. The fullerene coating provided long-term stable operation of single-tip tungsten emitter during their operation in high-voltage modes (5–10 kV) in technical vacuum (10^{-7}–10^{-8} Torr).

Fullerene coatings have a large work function (about 5.3 eV) [9]. To lower the work function of coating is possible by depositing onto its surface thin coating (of the order of a monolayer) of a substance with a smaller work function. Studies have shown that the deposition of potassium atoms leads to a drop to 3.5–4 times the magnitude of the characteristic voltage needed to obtain a fixed current. However, after completion of the activation process, the characteristic voltages increase within 15–20 hours practically to the initial value due to the departure of potassium atoms from the surface towards the substrate. The long-term decrease in the work function was achieved by activating the fullerene coating not by atoms, but by the flow of slow (40–100 eV) potassium ions [9, 10]. With this activation method, metallofullerenes such as endohedrals ($K@C_{60}$) and / or exohedrals ($C_{60}@K$) [11] are formed in the coating, the presence of which in the coating reduces the work function of its surface. The maximum decrease in the work function of the coating when activated by the ion flow reached approximately 1.5 eV.

Molecules of metallofullerenes have a large dipole moment and in inhomogeneous electric fields in the presence of even small inhomogeneities of coating move towards the large electric fields, forming a lots (tens) of nano-protrusions on the surface of the submicron tip. This structure of the protrusions gives additional field amplification at the surface of the tip emitter.

The carried out experiments demonstrated a peculiar self-regulation process of the structure of the protective fullerene layer in the presence of an intense ionic bombarding. Fast ions bombarding the emitter practically do not destroy or desorb the coating molecules, and most of their energy is released in the substrate. On the way to the substrate, they destroy some protrusions on the surface of the coating, but the polarized molecules of fullerenes and metallofullerenes released from the protrusions move along the surface of the emitter under the influence of highly inhomogeneous fields and are quickly captured by neighboring protrusions or form new ones. As a result, the emission currents fluctuate, but their average values vary slightly with time. Rapid movements of dipole molecules over the surface lead to flickering of the image of the emitting surface of the tip, which is recorded on the screen of the field emission projector.

Thus, the data obtained by us earlier show that thin fullerene coatings allow to protect the tungsten tip field emitter from the destructive effect of ion bombardment. This method of protection is fairly simple and reproducible. However, single-tip field emitters with a submicron top radius, even of such a firm and refractory material as tungsten, cannot provide field emission currents in excess of 100–200 μA. Therefore, it is of great interest to consider the possibility of creating distributed multi-tip cathodes with fullerene coatings.

1.2. Multi-tip silicon field emitters with protective coatings. As the experience of field emitters shows, it is possible to obtain currents of the order of tens of milliamperes required in many applications only from distributed systems of a sufficiently large area. Therefore, it was decided to determine the possibility of creating and using multi-tip field emitters with protective coatings.

A fairly simple technology for creating ordered multi-tip systems of silicon has long been well developed (see, for example, [12]). However, the use of such systems as emitters is difficult, not only because they are destroyed by the ion bombardment, but also because the silicon tips are usually of low conductivity. In addition, silicon emitters are often not strong enough and are destroyed under the action of ponderomotive forces even at moderate values of the electric field and the emission current. The use of tip-like silicon field emitters in high-voltage electronic devices operating in a technical vacuum becomes possible if simultaneously to increase their conductivity and strength, as well as resistance to ion bombardment.

It is obvious that the conductivity of the surface of the silicon tip can be increased if even a thin (about 4–5 nm) layer of metal is deposited on it (see, for example, [13]). The creation of a thicker layer of metal on the surface of the tip can also increase its strength. However, metallization is not capable of permanently protecting the emitter from the destructive effect of ion bombardment. It was decided to test the possibility of simultaneous solution of all the main problems preventing the use of multi-tip cathodes from silicon by means of two-layer metal-fullerene coatings [14–16]

To increase the conductivity and strength of multi-tip silicon emitters, molybdenum coatings were created. To protect against the destructive effect of ion bombardment, a coating of fullerene C_{60} molecules was deposited on the surface of the metallization layer. The work of silicon multi-tip cathodes with such double-layer coatings was investigated. The cathodes had different morphologies of the surface. The radius R of the top of the silicon tip and their height h varied for different samples within $5 \leq R \leq 20$ nm, $10{\leq}h{\leq}60$ µm, respectively. The distance L between the tips varied within $0.25h{\leq}L{\leq}2h$. The thickness of the molybdenum coating varied from about 5 to 20 nm. A further increase in the thickness of the molybdenum coating could lead to an unacceptable increase in the characteristic voltage necessary to obtain a fixed field emission current. The thickness of fullerene C_{60} molecules coating varied from 2 to 10 ml.

The cathodes created on the basis of flat silicon multi-tip structures are necessary for the formation of homogeneous cross sections and annular electronic flows with axial symmetry, that is, flows destined for use in basic types of electron-beam microwave devices, such as, for example, gyrotrons, TWTs and BWOs. In the cathodes that are homogeneous over the cross-section, their outer diameter and the area of the emitting surface were varied within wide limits. In the annual emitters, in addition, the width Δ of emitting belt was changed.

Along with the experimental study of multi-tip cathodes, calculations were made aimed at optimizing the morphology of their surface. The calculations determined the effect on the magnitude of the field emission current of height h and radius R of the top of the tip, and also the distance L between them. The calculations were performed for a diode system with infinitely extended flat cathodes and an anode located at a distance of 1.5 mm from each other. The voltage U between the cathode and the anode of the diode structure varied in the calculations within $1 \leq U \leq 20$ kV. In the calculations, a conical shape of the tips with a fixed base radius of 5 µm was set. For cathodes with an activated metal-fullerene coating, the work function of the tips was set in the range from 4.0 eV to 4.7 eV. For non-activated coatings, the work function was taken equal to 5.3 eV.

In the given geometry, for different values of the voltage U, the three-dimensional Laplace equation was numerically solved using the finite element method using the COMSOL Multiphysics software package [17]. Based on the obtained potential distribution data the distribution of the electric field E at the tip surface was determined, and then the distribution of the field emission current density from their surface and the current from each tip were calculated using the Fowler–Nordheim formula. To obtain the total current from the cathode, the total current was summed over all the tips from which the electrons hit the collector.

Two types of uniform over surface multi-tip cathodes were experimentally investigated: small area cathodes (SAC) and large-area cathodes (LAC). Multi-tip structures of the SAC were formed on the end surface of silicon rode with the diameter 1 mm facing to anode and had an area of 0.002 cm^2. The LACs were formed on flat silicon substrates with an area from 0.1 to 1.0 cm^2. The SACs included from 1 to 300 tips. The number of tips on the surface of the LAC reached about 10^5. The image of a section of the surface of the LAC obtained in a scanning electron microscope and the image of a single tip are shown in Fig. 1.

The investigated annular emitters had approximately the same area (0.3 cm^2) and the morphology of the emitting surface and differed by the mean diameter and width of the multi-tip belt. All coatings were deposited on the multi-tip structures directly in the experimental device. Here, the fullerene coatings were activated by the flow of potassium ions with an energy of 40 eV. The morphology of the surface of the field emitters was monitored using a scanning electron microscope type Supra 45 WDXC before installation in the experimental device and after the end of the experiments.

The vacuum chamber, in which the experimental studies were carried out, was continuously pumped using a magnet-discharge pump. It was equipped with a nitrogen inlet system. Nitrogen inlet allowed to quickly change the pressure in the chamber from a minimum of 10^{-10}–10^{-9} Torr to 10^{-6} Torr and back. Formation of coatings was carried out, as a rule, at pressures of the order of 10^{-9} Torr. To obtain information on the functioning of cathodes in a technical vacuum, the emission characteristics of cathodes were measured at increased pressures of about 10^{-7} Torr.

The characteristics of the SAC were experimentally studied in a field emission microscope projector with a distance between the cathode and the anode collector 12–15 mm. Because of the «defocusing» of the electron beam on the path from the tip structure to the collector, the density of the electron current to the collector did not exceed about 10^{-3}–10^{-4} of the average surface current density from the cathode. In connection with this, during the investigation of the SAC, it was possible to determine the possibility of durable operation of cathodes in a continuous mode when taking of sufficiently high current densities from their surface, minimizing the intensity of electron bombardment of

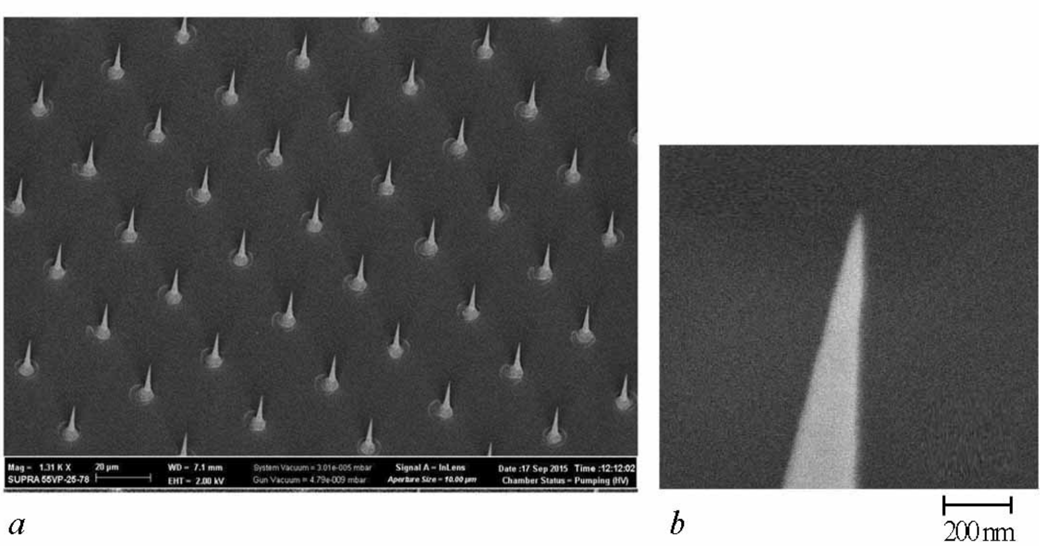

Fig. 1. *a* – an image of a part of the surface of a large area cathode, obtained with a scanning electron microscope (recorded at an angle of 45° to the normal of the emitter surface). The distance between the tips is 30 μm, the height of the tips is 30 μm. *b* – image of the single tip

the collector and the thermal effects on the collector, as well as the desorption of particles from its surface.

Typical characteristics of the SAC are shown in Fig. 2. The investigated SAC had approximately 300 silicon tips with a coating including a layer of molybdenum approximately 10 nm thick and deposited over the metallization fullerene coating with a thickness of 2 ml, activated as a result of the bombardment with potassium ions. The radius of the tip top with allowance for the coverage was approximately 20 nm.

Measurements of the emission characteristics of the LAC and annular emitters were carried out in a diode with a distance of 1.5 mm between the cathode and the collector-anode. The densities of the recorded currents on the collector in such measurements are close to the current density from the cathode. Therefore, in order to avoid overheating of the collector, the main measurements of the characteristics of the LAC and annular emitters in a continuous mode were carried out at emission currents not exceeding 1–2 mA. Measurements at higher currents were performed in a pulsed mode with a pulse duration of 1–2 μs and a repetition rate of 50–500 Hz.

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The current-voltage characteristic $I(U)$, measured in the pulsed mode, is shown in Fig. 2, *a*. The average over the surface of the SAC emission current density at an extreme current of approximately 2 mA was of the order of 1 A/cm^2. A typical dependence of the emission current of the SAC on the cathode operating time $I(t)$, measured at a voltage $U = 6.3$ kV and an initial current of 240 μA, is shown in Fig. 2, *b*.

Experiments with cathodes of small area confirmed the possibility of protection of field emitters with the help of metal-fullerene coatings against destructive ion bombardment. In a technical vacuum at the level of 10^{-7} Torr, current fluctuations did not exceed approximately ± 2–3 %. When measuring characteristics $I(t)$, the maximum time interval of operation of the SAC for one day did not exceed 5–7 hours. However, the

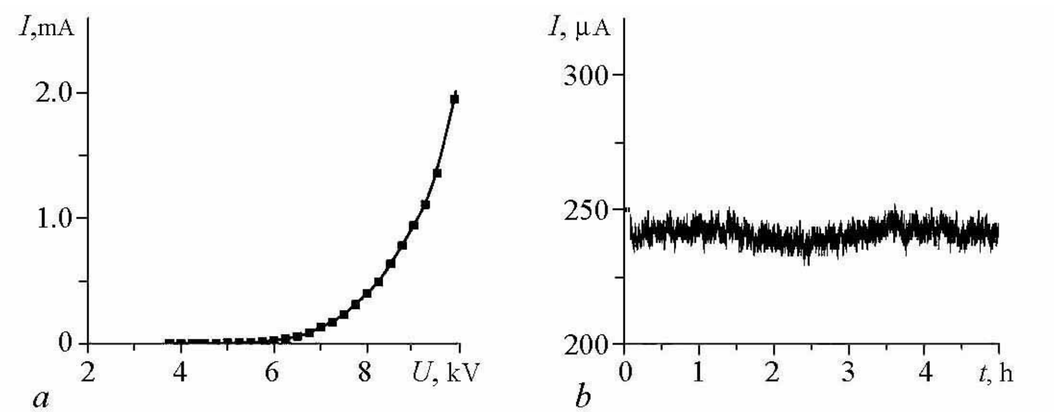

Fig. 2. Characteristics of a small area cathode with a metal fullerene coating: *a* – current-voltage characteristic of a cathode obtained in a pulsed mode (2 μs, 100 Hz); *b* – the dependence of the emission current on the operating time in the static mode at a voltage $U = 6.3$ kV

high durability of the field emitters during operation in a technical vacuum is confirmed by the multiple long-term measurements of the characteristics $I(t)$ of the given cathode, performed in different days.

The obtained data on the emission characteristics of SAC with two-layer coatings indicate that emitters of this type can operate stably in a continuous mode at emission current densities sufficient for some types of short-wave (millimeter and submillimeter wavelengths) microwave devices. For example, even with an emission current of 240 μA, which is substantially lower than the maximum value (about 2 mA), the average emitter surface density of the emission current was about 1.2×10^{-1} A/cm^2.

In the experiments with the SAC, the maximum values of the emission current were estimated, which can withstand a single silicon tip with a two-layer metal-fullerene coating. It was found that a typical tip with a coating, having a total radius of the top (taking into account the thickness of the coating) 20–25 nm, can withstand current not more than 5–6 μA. The possibility of obtaining higher currents was investigated for cathodes of large area.

The data obtained during the investigation of the SAC were used in calculation of determining the optimum morphology of the surface of multi-tip cathodes.

Considering the fact that the tips of existing silicon cathodes can withstand currents not exceeding a certain limiting value I_{extrem}, when choosing the optimal morphology of the surface of multi-tip cathodes for high-voltage devices, a compromise solution must be made. On the one hand, to obtain a current I from the cathode, a sufficiently large number of tips N satisfying the relation $N \geq I/I_{\text{extrem}}$ on its surface should be created on its surface, and on the other hand, the operation of the electronic device should be provided at an increased operating voltage. To adopt such a compromise solution, data are needed on the effect of the morphology of the surface of multi-tip cathodes on value of current from their surface. Fig. 3 shows a family of calculated volt-ampere characteristics for multi-tip emitters with a non-activated metal-fullerene coating ($e\varphi = 5.3$ eV) having tips height $h = 30$ μm and a tip radius $R = 10$ nm obtained for different values of the distance L between the tips.

From the data obtained it follows that under conditions where there is practically no mutual screening of the tips (at L=2h=60 μm), an emitter of 0.2 cm^2 can provide currents of not more than 50 mA. Larger currents can be obtained from an emitter of the same area, but with a larger number of tips on the surface and with a greater voltage between the cathode and the anode. The choice of the ratio of the height of the tips and the distance between them determines the permissible value of the voltage U when operating the cathode. The calculations show that, for example, at U=17 kV, the structure of tips with a height of 30 μm at L=0.5h can provide field emission currents of about 0.8 A.

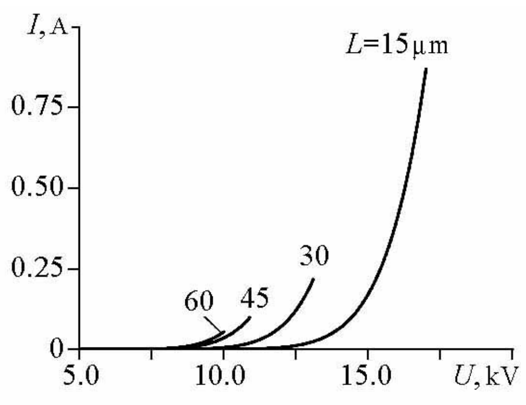

Fig. 3. A family of current-voltage characteristics of emitters with a non-activated metal-fullerene coating ($e\varphi = 5.3$ eV). Calculation were made for emitters with $h = 30$ μm and $R = 10$ nm having the structures with different values of the distance L between the tips

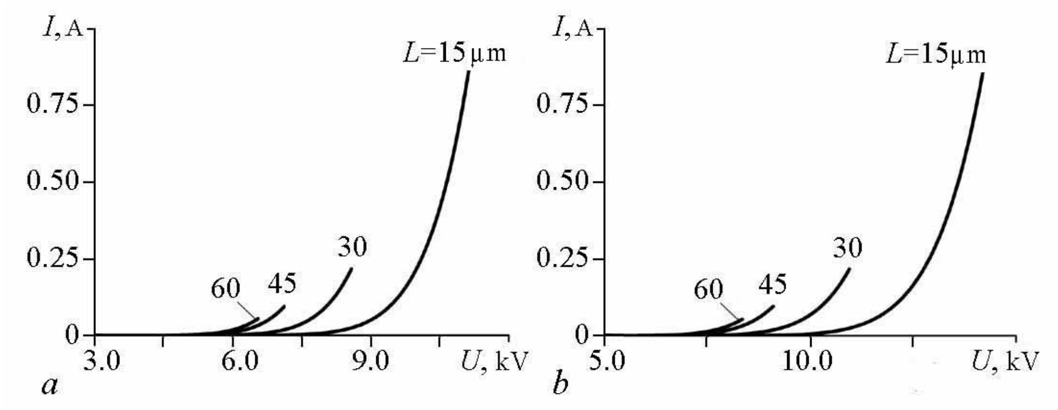

Fig. 4. A family of current-voltage characteristics of emitters with an activated metal-fullerene coating: a – $e\varphi = 4.0$ eV; b – $e\varphi = 4.7$ eV. Calculation were performed for emitters with $h = 30$ μm and $R = 10$ nm for structures with different values of the distance L between the tips

To reduce the operating voltages required for obtaining fixed values of currents, it is possible, if we use activated metal-fullerene coating. Fig. 4, a shows a family of current-voltage characteristics for emitters with $R = 10$ nm, $h = 30$ μm and different values of L obtained for an activated metal-fullerene coating with work function of 4.0 eV. Fig. 4, c shows a family of characteristics obtained for an activated coating with a value of $e\varphi = 4.7$ eV. According to the calculations, using an activated coating can reduce the voltage required to obtain a fixed value of the emission current, by a factor of 1.5.

In these calculations the possible limitations of the emission current of multi-tip cathodes, due, for example, to the finite strength of the tips and thermal effects (their finite thermal conductivity) was not taken into account. For such complex nano-structured systems, such as the tip with two-layer metal-fullerene coatings, it is practically impossible to accurately determine these characteristics. In calculations it is also difficult to take into account the fine structure of the protrusions on the surface of the fullerene coating, the formation of which can significantly change the field amplification. It is possible to obtain information on the influence of these factors practically only in experiments.

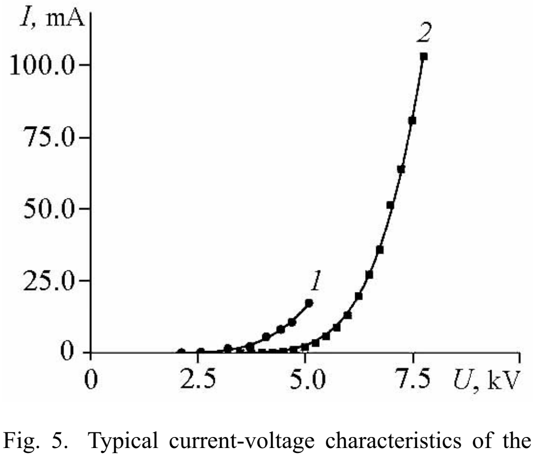

Fig. 5. Typical current-voltage characteristics of the large area cathode with activated (curve *1*) and with non-activated (curve *2*) coating

The results of an experimental study of LACs and annular-type emitters satisfactorily agree with the results of calculations. The best emission characteristics were obtained for LACs and annular emitters with tip height $h = 30$ μm and tip top radius R=20–25 nm located at a distance $L \approx h$, that is, under conditions of partial mutual screening of the tips. The work of cathodes with activated and non-activated coatings was experimentally investigated. After a long (several hours) training of cathodes with current taking off, the uniformly distributed over the surface of the LAC and the annular-type emitters worked stably under the conditions of a technical

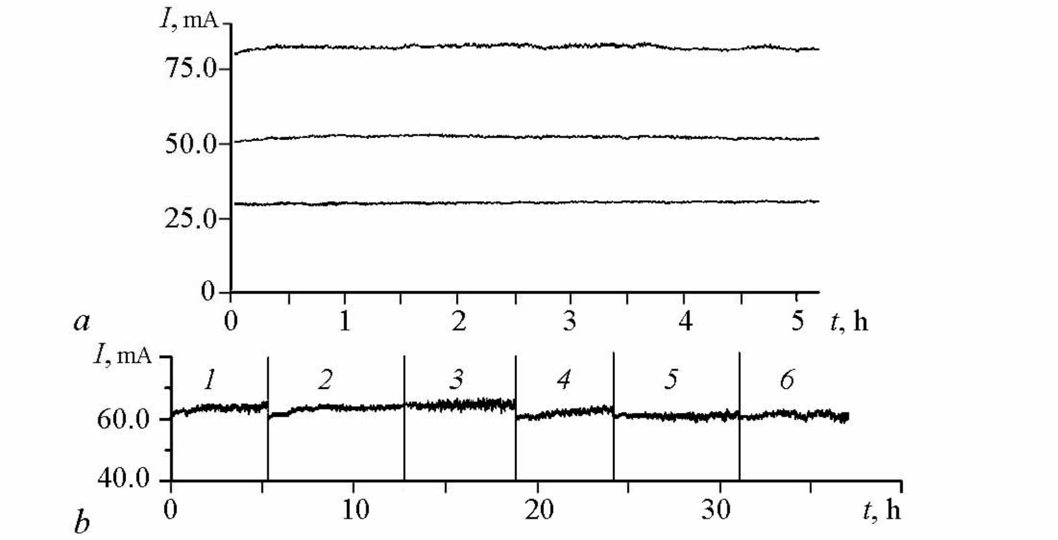

Fig. 6. Measured in the pulsed mode (1 μs, 500 Hz) the dependences of the emission current I of the annular cathode with an external diameter of 8.3 mm and an internal diameter of 5.7 mm on the operating time (t, hour): *a* – the characteristics measured at different initial emission current values; *b* – a typical sequence of $I(t)$ curves measured for one emitter for 6 days (*1–6*) at the voltage of 9.9 kV and approximately the same values of the initial emission current

vacuum. The extreme emission currents of nonactivated LACs with an area of 0.2–0.3 cm^2 and annular cathodes of the same area reached values of 100–110 mA. Figure 5 shows typical current-voltage characteristics of a LAC with an area of 0.25 cm^2 with an activated coating (curve *1*) and with a non-activated (curve *2*) coating. The extreme currents of the LAC with activated coating were significantly less than when working with the non-activated coating. From our point of view, the drop in the extreme currents is due to the fact that when the coating is activated, some of the potassium atoms not captured by the fullerene molecules intercalate under the fullerene coating and reduce its bond with the substrate.

The high stability of the operation of the LAC and annular emitters is evidenced by the dependence of the emission current measured on these cathodes on the time of their operation. Typical dependences $I(t)$ measured for one of the annular emitters of 0.3 cm^2 are shown in Fig. 6, *a*. As in the case of cathodes of small area, the high stability of the operation of the LAC is confirmed by measurements of the $I(t)$ characteristics of such cathodes performed on different days. Fig. 6, *b* shows a typical sequence of dependencies $I(t)$, measured for one annular emitter for 6 days. Vertical lines indicate the beginning of measurements, and above the curves the days are numbered during which measurements were taken. Thus, summarizing the results of the study of multi-tip silicon cathodes with two-layer metal-fullerene coatings, we note the main point.

- There has been worked out technology of creating metal-fullerene coatings on the surface of multi-tip silicon structures that is quite easily in the implementation.
- In the calculations carried out, the criteria for optimizing the morphology of the structure surface have been worked out.
- The experiments demonstrated the possibility of stable operation of multi-tip cathodes with metal-fullerene coatings in high-voltage electronic devices under conditions of a technical vacuum at the level of 10^{-7} Torr.

- From the optimized multi-tip cathodes, area 0.2–0.3 cm^2 with protective metal-fullerene coatings, emission currents of about 100 mA are obtained, sufficient for the operation of certain types of microwave devices in the short-wave millimeter and submillimeter range, as well as miniature X-ray sources.

2. Multilayer cathodes are a new type of emitters whose field emission is determined by the fields at the contact of materials with different work functions

To obtain intense field emission, it is necessary to create extremely large electric fields on the surface of a solid of order or more than (2–5)$\cdot 10^7$ V/cm. Usually, to obtain such fields at moderate voltages on the surface of cathodes, field-amplification protrusions or protrusion structures are created. Formation of the structure of the protrusions, which provide sufficient amplification of the field, is a complex technological task. In addition, they are destroyed under the action of ponderomotive forces and / or ion bombardment in the first place. Meanwhile, it is known (see the example, [18]) that large electric fields exist at the contact of materials with different work functions $e\varphi$. It is generally believed that the effect of such fields adversely affects the emission of cathodes. For example, «spot fields» existing on the surface of materials that are inhomogeneous in chemical composition reduce the effective emitting surface, preventing the exit of thermo-electrons from the cathode in the contact areas of different materials [18].

We decided to test the possibility of obtaining field emission under action of contact fields. The composites from the hexaboride lanthanum ($e\varphi \approx 2.5$–3.8 eV) granules in pyrography ($e\varphi \approx 4.7$ eV), and also the simplest systems from the indium ($e\varphi \approx 3.7$–4.1 eV) [19] and fullerenes ($e\varphi \approx 5.3$ eV) [8] layers brought into contact were studied. These studies demonstrated the possibility of obtaining field emission from the contact of materials with different work functions. The results obtained served as the basis for the development of multilayer emitters of a new type [15, 20].

Multilayer systems, including a large number (up to 40) of contact pairs of layers of materials with different work functions, seemed promising for obtaining large field emission currents. Multilayer cathodes from two pairs of materials: from ytterbium ($e\varphi \approx 3.1$ eV) and carbon ($e\varphi \approx 4.7$ eV), as well as from hafnium ($e\varphi \approx 3.5$ eV) and platinum ($e\varphi \approx 5.3$ eV) were studied. Layered cathodes were created using magnetron sputtering.

We will present here the results of recent studies of the most effective layered Hf-Pt cathodes. Special calculations and experiments were carried out to develop rules for constructing layered cathodes and determining their emission characteristics. In performed calculations using the program COMSOL Multiphysics, the field distributions in a diode system with a layered cathode were determined. Then, electron trajectories were built, and currents to the anode were determined. Existence of transition zones between the contacting layers, where a mixture of materials is formed during the successive magnetron sputtering, was taken into account when calculating the fields.

The calculations determined the effect on the emission characteristics of layered cathodes of the thickness d of the layers brought into contact and the difference in their work function of $\Delta e\varphi$, as well as the number of pairs of layers N. Fig. 7 shows the

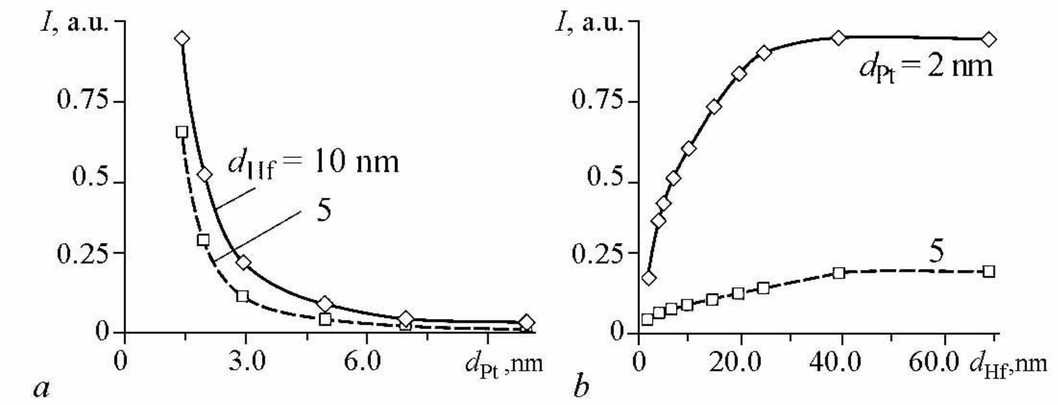

Fig. 7. *a* – dependences of the emission current I on the thickness d_{Pt} of platinum layers at fixed values of the hafnium layers thickness d_{Hf}. *b* – dependences of the emission current on the thickness of hafnium layers at fixed thickness of platinum layers. The calculations were performed at the anode voltage $U = 6$ kV for the cathode including 20 pairs of layers of hafnium and platinum

calculated characteristics of cathode containing 20 pairs of hafnium and platinum layers. Calculations have shown that an increase in the thickness of platinum layers d_{Pt} at a fixed thickness of the layers of hafnium d_{Hf} leads to a rapid drop in the emission current (Fig. 7, *a*). An increase in the thickness of hafnium layers in the interval $d_{\mathrm{Hf}} \leq$ 20–25 nm at $d_{\mathrm{Pt}} = \mathrm{const}$ is accompanied by a rapid increase in the emission current (Fig. 7, *b*). Then, the current growth slows down and the dependence $I(d_{\mathrm{Hf}})$ becomes saturated.

It follows from the calculations (Fig. 8) that at a given total thickness d_{Σ} of the layered cathode and a minimum thickness of platinum layers $d_{\mathrm{Pt}} = 2$ nm, in order to obtain the maximum emission current, optimization of the thickness of the hafnium layers is necessary. So at $d_{\Sigma} = 250$ nm, the optimal thickness of hafnium is 10–12 nm. Experimental study of the operation of multilayer cathodes confirmed the main conclusions that follow from the calculations. Measurement of emission characteristics was carried out in a diode with a distance of 1 mm between the cathode and the anode. Fig. 9, *a* shows the typical current-voltage characteristic and the Fowler–Nordheim characteristic of the Hf-Pt cathode. Fig. 9, *b* shows the dependence of the emission current I of the same cathode on the time t of its operation. The cathode included 20 pairs of layers of platinum and hafnium with thicknesses of 2 and 10 nm, respectively. Such a cathode provided in continuous mode a field emission current of up to about 2 mA with an average current density of about 200 A/cm^2.

When working with layered cathodes, it is impossible to use any coating that protects the emitter from the destructive effect of ion bombardment. However, experiments have shown that even with these extremely high current densities in a technical vacuum within 10^{-7}–10^{-8} Torr Hf-Pt, cathodes work almost as stably as multi-tip silicon cathodes with protective metal-fullerene coatings. As in the case of multi-tip cathodes with metal-fullerene

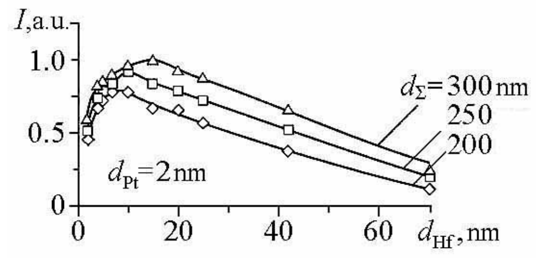

Fig. 8. Dependences of the emission current of a multilayer cathode on the thickness of hafnium layers d_{Hf}, calculated for cathodes of different total thickness d_{Σ} at a fixed thickness of platinum layers $d_{\mathrm{Pt}} = 2$ nm. Anode voltage $U = 6$ kV

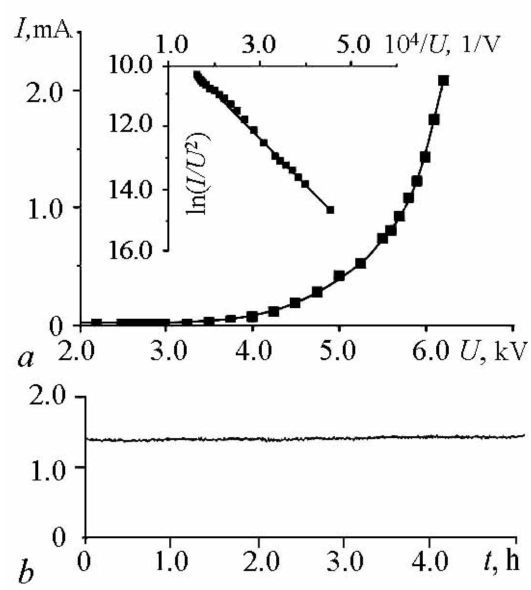

Fig. 9. Characteristics of a multilayer cathode including 20 pairs of hafnium and platinum layers: *a* – the current-voltage and Fowler–Nordheim characteristics; *b* – typical dependence of the emission current on the operating time

coatings, stability tests of multilayer cathodes were carried out for a period of no more than 5–7 hours per day. However, measurements performed over several days indicate that the emission characteristics of layered cathodes remain practically unchanged, at least for several dozen hours of operation. Such a stable operation of layered cathodes under conditions of intense ion bombardment can be explained by the fact that the sputtering of the surface of the investigated layered structure practically does not change the dimensions of the contact area of the deposited materials, and also their work functions. The change in the distance between the emitting surface of the layered structure and the anode associated with sputtering is negligible compared to the initial value of this distance $d = 1$ mm.

Conclusion

Summarizing the work, we note the following.

- In many laboratories around the world, field emitters are being developed and investigated. At present, cathodes already exist that can provide sufficiently high currents and densities of field emission currents, which are necessary for a number of applications in microwave electronics. However, so far, for most existing cathodes, the possibility of their practical use in high-voltage electronic devices operating in technical vacuum is not proved. Promising for such applications are those developed in SPbPU multi-tip silicon cathodes with two-layer metal-fullerene coatings, as well as multilayer cathodes from the materials with different work functions brought into contact.
- The data obtained in SPbPU indicate the possibility of using the investigated multi-tip cathodes in miniature high-voltage devices operating in a technical vacuum. Created multi-tip cathodes with protective metal-fullerene coatings provide stable emission, sufficient for diagnostic gyrotrons [1]. Multilayer cathodes do not yet allow us to obtain the currents necessary for the operation of this type of microwave devices, but according to estimates, they have large reserves of increasing emission currents. Both types of cathodes, developed and studied in SPbPU, are already promising for use in miniature X-ray sources at this stage.

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References

1. Glyavin M.Yu., Manuilov V.N., Sominskii G.G., Taradaev E.P., Tumareva T.A. The concept of an electron-optical system with field emitter for a spectro-scopic gyrotron. *Infrared Physics & Technology*, 2016, vol. 78, pp. 185–189.
2. Burtsev A.A., Grigor'ev Yu.A., Danilushkin A.V., Navrotskii I.A., Pavlov A.A., Shumikhin K.V. Features of the development of electron-optical systems for pulsed terahertz traveling wave lamps: Review. *Tech. Phys.*, 2018, vol. 63, iss. 3, pp. 452–459.
3. Whaley D.R., Duggal R., Armstrong C.M., Bellew C.L., Holland C.E., Spindt C.A. 100 W operation of a cold cathode TWT. *IEEE Transactions on Electron Devices*, 2009, vol. 56, no. 5, pp. 896–905.
4. Spindt C., Holland C. E., Schwoebel P. R.. A reliable improved Spindt cathode design for high currents. *Vacuum Electronics Conference, 2010 (IVEC–2010), IEEE International,* 2010, May, pp. 201–202.
5. Chen Z., Zhang Q., Lan P., Zhu B., Yu T., Cao G., den Engelsen D. Ultrahigh-current field emission from sandwich-grown well-aligned uniform multi-walled carbon
nanotube arrays with high adherence strength. *Nanotechnology*, 2007, vol. 18, pp. 265702.
6. Bushuev N. A., Glukhova O. E., Grigor'ev Yu. A., Ivanov D. V., Kolesnikova A.S., Nikolaev A.A., Shalaev P.D., Shesterkin V.I. Emissivity of a multibeam electron gun with a glassy carbon field-emission cathode. *Tech. Phys.*, 2016, vol. 61, iss. 2, pp. 290–295.
7. Aban'shin N. P., Gorfinkel' B. I., Morev S. P., Mosiyash D.S., Yakunin A.N. Autoemission structures of nanosized carbon with ionic protection. Studying the prospects of reliable control in forming structures. *Tech. Phys. Letters*, 2014, vol. 40, iss. 5, pp. 404–407.
8. Tumareva T. A., Sominskii G. G., Efremov A. A., Polyakov A. S. Tip field emitters coated with fullerenes. *Tech. Phys.*, 2002, vol. 47, iss. 2, pp. 244–249.
9. Tumareva T. A., Sominskii G. G., Bondarenko A.K., Veselov A.A., Svetlov I.A. Activation of fullerene coatings on field emitters by potassium atom and ion fluxes. *Tech. Phys.*, 2006, vol. 51, iss. 7, pp. 898–901.
10. Tumareva T.A., Sominskii G. G., Svetlov I. A., Morozov A. N. Fullerene-coated field emitters activated by a potassium ion flux in high electric fields. *Tech. Phys.*, 2008, vol. 53, iss. 11, pp. 1504–1507.
11. Campbell E.E.B., Tellgmann R., Krawez N., Hertel I.V. Production and LDMS characterisation of endohedral alkalifullerene films. *Journal of Physics and Chemistry of Solids*, 1997, vol. 58, iss. 11, pp. 1763–1769.
12. Givargizov E.I. Crystal whiskers and nano-tips. *Nature*, 2003, iss. 11, pp. 20–25 (in Russian).
13. Karabutov A.V., Konov V.I., Pimenov S.M., Frolov V.D., Obraztsova E.D., Polyakov V.I., Rossukanyi N.M. Peculiarities of field electron emission from CVD diamond films. *J. De Physique IV*, 1996, vol. 6, iss. 5, pp. C5113–C5118.
14. Sominskii G.G., Tumareva T.A., Taradaev E.P., Mishin M.V., Stepanova A.N. Mul-

titip semiconductor field emitters with new-type bilayer protecting coatings. *Tech. Phys.*, 2015, vol. 60, iss. 1, pp. 133–141.

15. Sominskii G.G., Sezonov V.E., Taradaev E.P., Tumareva T.A., Zadiranov Y.M., Kornishin S.Y., Stepanova A.N. Innovative field emitters for high-voltage electronic devices. *Radiophysics and Quantum Electronics*, 2015, vol. 58, iss. 7, pp. 511–519.
16. Sominskii G.G., Taradaev E.P., Tumareva T.A., Mishin M.V., Stepanova A.N. Field emission of multitip silicon structures with protection coatings. *Tech. Phys.*, 2016, vol. 61, iss. 11, pp. 1711–1714.
17. COMSOL Multiphysics. Platform for modeling physical processes [Electronic resource]. https://www.comsol.ru/comsol-multiphysics.
18. Dobretsov L.N., Gomoyunova M.V. Emission Electronics. Moskow: Nauka, 1966, 564 p. (in Russian).
19. Fomenko V.S. Emission Properties of Materials: A Hand book. Kiev: Naukova Dumka, 1981, 339 p. (in Russian).
20. Sominskii G.G., Sezonov V.E., Tumareva T.A., Taradaev E.P. Field Emitter. Patent of the Russian Federation N_0 118119 for utility model. Published on 10.07.2012.